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From Cyclopropenes to Tetrasubstituted Furans: Tandem Isomerization/Alkenylation Sequence with Cu/Pd Relay Catalysis

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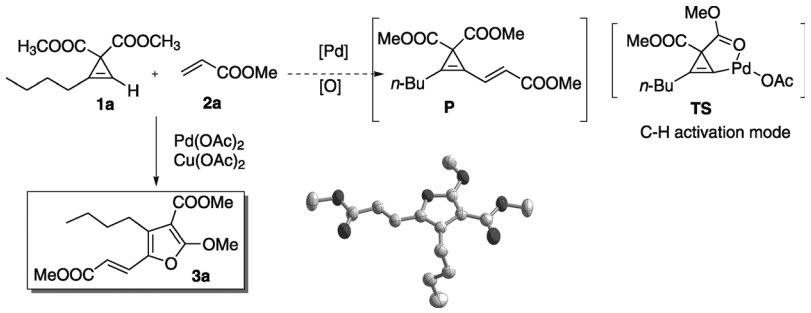
Furans represent an important class of five-membered heterocycles that are prevalent in a number of biologically active natural products and pharmaceuticals.[1] They are also useful building blocks in organic synthesis.[2] Thus, many synthetic methods[3] have been developed for the synthesis of furan rings, such as the condensation of 1,4-dicarbonyl compounds (Paal–Knorr synthesis)[4] and the Feist–Benary synthesis.[5] However, these methods suffer from their inability to provide furans that contain sensitive functional groups with high flexibility. Therefore, new and efficient methods for the synthesis of polysubstituted functionalized furan derivatives from simple and readily available starting materials under mild reaction conditions are of significant value.



Scheme 1. Intermolecular dehydrogenative Heck reaction of cyclopropene **1a** with alkene **2a**.

The current furan syntheses can be generally divided into two categories: The first involves the construction of the heterocyclic core by the cyclization of acyclic substrates. For example, several groups have developed efficient syntheses of furan compounds by the metal Lewis acid promoted cycloisomerization of alkynyl, allenyl, and cyclopropenyl substrates.[6] However, this method requires the synthesis of complicated starting materials and is limited by its unpredictable regioselectivity. The second category involves the introduction of functional groups onto an existing furan ring.[7] Herein, we report a new method that combines these two categories in a one-pot cycloisomerization/functionalization cascade by employing an intermolecular dehydrogenative Heck reaction (DHR) between a cyclopropene and an alkene. This intermolecular approach allows for the construction of alkene-functionalized tetrasubstituted furans[8] with high diversity (Scheme 1).

The intermolecular dehydrogenative Heck reaction[9] has emerged as an attractive and powerful method for the coupling of Ar–H groups and alkenes. In this process, a C–C bond is formed from two C–H bonds, thereby eliminating the arene-activation step in the classic Heck reaction. This reaction has received great interest over the past few years. Different transition metals, including Pd,[10] Ru,[11] and Rh,[12] can catalyze this process. Previous research has focused on the incorporation of new directing groups, coupling with unactivated alkenes, tuning regioselectivity by elaborating different ligands, and so on. The general mechanism in all of these processes is initiated by the directed or non-directed insertion of the metal into the C–H bond, thereby generating a carbon–metal species, followed by the normal Heck process, and finally the regeneration of the metal catalyst by the oxidant. Because the first electrophilic metal insertion into the C–H bond requires high activation energy, these reactions usually require harsh conditions, such as high temperature, a strong acid additive, and prolonged reaction time. We proposed that, if we can avoid this direct C–H metalation step but use another method to form the key carbon–metal species, the reaction efficiency can be greatly improved.

Cyclopropene shows unique and interesting reactivities in the presence of a transition metal because of its tremendous ring strain.[13] In our attempts to generate 1,1,2,3-tetrasubstituted cyclopropenes through DHRs between cyclopropene **1a** and an alkene, based on an ester-group-directed C–H activation process,[14] to our surprise, we did not isolate any

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1,1,2,3-tetrasubstituted cyclopropene (**P**) under our optimized reaction conditions. Instead, tetrasubstituted furan **3a** was obtained, as confirmed by X-ray diffraction and NMR spectroscopy (Scheme 1). A mechanistic study indicated another Cu/Pd relay catalytic sequence that was different from the general C–H metalation process. Herein, we report our preliminary results.

Initially, we explored the viability of this DHR process in the reaction of cyclopropene **1a** with methyl acrylate (**2a**). Gratifyingly, the use of $Pd(OAc)_2$ (5 mol%) as the catalyst and $Cu(OAc)_2$ (2 equiv) as the oxidant at 60 °C in MeCN afforded a major product in 21% yield. NMR and MS data were in accord with the formation of the DHR product (**P**), except that the resonance of the two methyl ester groups from the cyclopropene was shifted. This puzzling question was not finally resolved until we obtained the X-ray crystal structure of the product. Indeed, the product was not cyclopropene **P**, but instead isomerized tetrasubstituted furan **3a** (Scheme 1).[15]

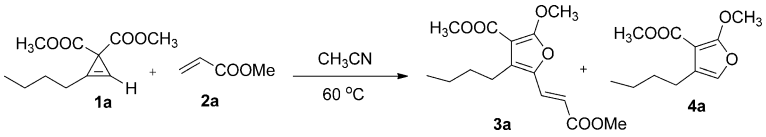
Inspired by this result, we continued to optimize the reaction conditions to develop an efficient catalytic system for the synthesis of the all-substituted furan. We began our exploration by screening different oxidants and we found that only $Cu(OAc)_2$ and AgOAc gave promising results (Table 1, entries 1–6). The use of other oxidants (*tert*-butyl hydroperoxide, benzoquinone, $PhI(OAc)_2$, air; see the Supporting Information for details) resulted in no coupled product. Other copper salts, including $CuCl_2$, $CuSO_4$, and $Cu(ClO_4)_2$, were also ineffective as oxidants, which indicated that the counterion played an important role in the reaction (Table 1, entries 4–6). To our delight, when three equivalents of DMSO were added to MeCN as the additive, the efficiency of this reaction was greatly improved.[16] The reaction was complete within 1 h in 76% yield (Table 1, entry 7).[17] Increasing or decreasing the amount of DMSO did not lead to better results (Table 1, entries 8 and 9). Under some conditions, a small amount of trisubstituted furan **4a** was isolated as the by-product. Using other palladium catalysts (Table 1, entries 10–12) or changing the temperature to 40 °C and 80 °C (Table 1, entries 13 and 14) produced less-satisfactory results. Finally, the efficiency of the reaction was tested by using 1 mol% of the catalyst, which gave the product in 48% yield, along with the isomerized furan **4a** in 30% yield, after 30 min (Table 1, entry 15).

Control experiments confirmed that both the copper and palladium catalysts were necessary in this process. Only the isomerized product (**4a**) was formed without the palladium catalyst (Table 1, entry 16) and no product was formed without the copper catalyst (Table 1, entry 17).

With the optimal conditions in hand, that is, the use of $Pd(OAc)_2$ (5 mol%), $Cu(OAc)_2$ (2 equiv), and DMSO (3 equiv) at 60 °C in MeCN, we examined the scope of this transformation. A series of cyclopropenes were reacted with methyl acrylate and the results are summarized in Table 2. Both aromatic cyclopropenes and aliphatic cyclopropenes can all generate their corresponding products in moderate-to-good yields. An unsubstituted cyclopropene dicarboxylate substrate also provided 2,3,5-trisubstituted furan **3d** in 58% yield. Halogen atoms, such as Br and F, and a phenol group were tolerated in this reaction. The reaction of a cyclopropene that was derived from ethyl acetoacetate was more difficult in this transformation. Slow injection of the cyclopropene and increasing the palladium catalyst loading to 10 mol% afforded the 2-alkyl-tetrasubstituted furan (**3k**) in 53% yield. In addition, this reaction can be scaled up to the gram scale without showing a decrease in reaction efficiency and yield (see the Supporting Information).

Next, the scope of the alkene was explored (Table 3). A variety of electron-deficient alkenes, including different acrylates and *N*,*N*-dimethyl acrylamide, proceeded smoothly and efficiently to produce the corresponding products in generally good yields. More importantly, the reaction was successful for disubstituted alkenes, such as methyl crotonate (product **3p**) and methyl methacrylate (products **3q** and **3q′**). These results are remarkable, owing to the low reactivity of disubstituted alkenes.[18] In this case, the reaction does not require the addition of any ligand or much excess of the alkene and the coupled product can be formed in moderate yield within 2 h. With methyl methacrylate, only trace amounts of **3q′** was formed, according to ^{1}H NMR spectroscopy and TLC analysis (**3q**/**3q′**, 10:1), and the major isomer (**3q**) was formed

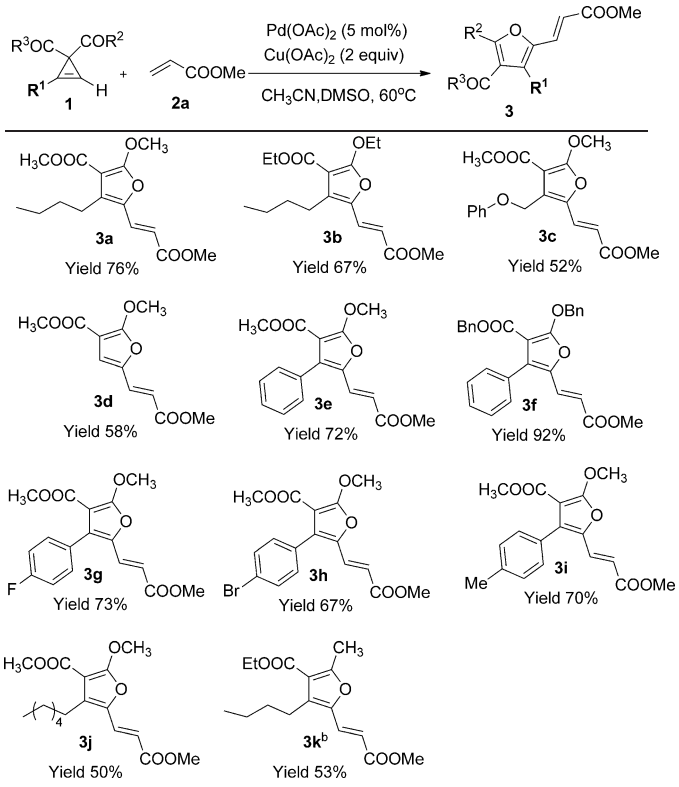
Table 1. Optimization of the reaction conditions.[a]



Entry	Catalyst	Oxidant	Additive (equiv)	Yield [%][b]
1	$Pd(OAc)_2$	$Cu(OAc)_2$	–	21
2	$Pd(OAc)_2$	BQ	–	0
3	$Pd(OAc)_2$	AgOAc	–	34
4	$Pd(OAc)_2$	$CuCl_2$	–	trace
5	$Pd(OAc)_2$	$CuSO_4$	–	trace
6	$Pd(OAc)_2$	$Cu(ClO_4)_2$	–	trace
7	$Pd(OAc)_2$	$Cu(OAc)_2$	DMSO (3)	76
8	$Pd(OAc)_2$	$Cu(OAc)_2$	DMSO (1)	65 (17)
9	$Pd(OAc)_2$	$Cu(OAc)_2$	DMSO[c]	31
10	$PdCl_2$	$Cu(OAc)_2$	DMSO (3)	60
11	$Pd(tfa)_2$	$Cu(OAc)_2$	DMSO (3)	76
12	$[Pd(PPh_3)_4]$	$Cu(OAc)_2$	DMSO (3)	42
13[d]	$Pd(OAc)_2$	$Cu(OAc)_2$	DMSO (3)	32
14[e]	$Pd(OAc)_2$	$Cu(OAc)_2$	DMSO (3)	58
15[f]	$Pd(OAc)_2$	$Cu(OAc)_2$	DMSO (3)	48 (30)
16[g]	–	$Cu(OAc)_2$	DMSO (3)	0 (68)
17[h]	$Pd(OAc)_2$	–	DMSO (3)	0

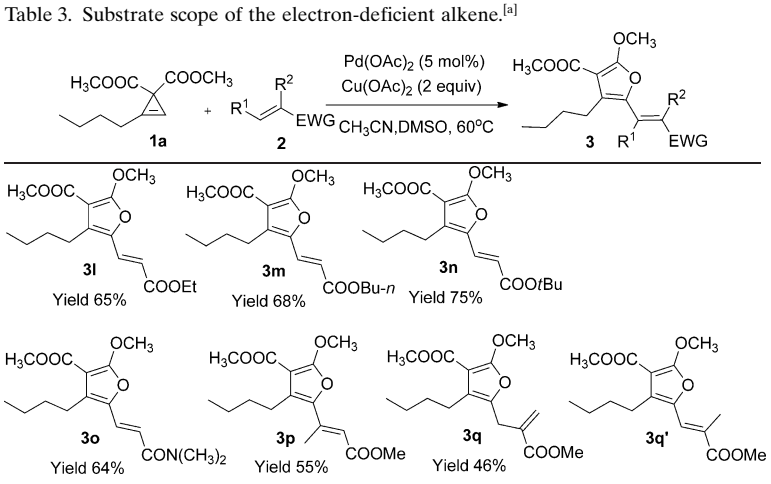
[a] Reaction conditions: cyclopropene **1a** (0.2 mmol), methyl acrylate (**2a**, 0.4 mmol), Pd catalyst (5 mol%), oxidant (0.4 mmol), MeCN (1 mL), 60 °C. [b] Yield of isolated product; the number in parentheses represents the yield of by-product **4a**. [c] DMSO was used as the solvent. [d] 40 °C. [e] 80 °C. [f] Catalyst (1 mol%), 30 min. [g] Only $Cu(OAc)_2$. [h] Only $Pd(OAc)_2$ (5 mol%) or $[PdCl_2(MeCN)_2]$ (5 mol%). BQ = 1,4-benzoquinone, TFA = trifluoroacetate.

Table 2. Substrate scope of the cyclopropene.[a]



[a] Reaction conditions: cyclopropene **1** (0.2 mmol), methyl acrylate (**2a**, 0.4 mmol), $Pd(OAc)_2$ (5 mol%), $Cu(OAc)_2$ (0.4 mmol), MeCN (1 mL), DMSO (0.6 mmol), 60°C. [b] With $Pd(OAc)_2$ (10 mol%) and slow injection of the cyclopropene over 1 h.

Table 3. Substrate scope of the electron-deficient alkene.[a]



[a] Reaction conditions: cyclopropene **1** (0.2 mmol), methyl acrylate (**2a**, 0.4 mmol), $Pd(OAc)_2$ (5 mol%), $Cu(OAc)_2$ (0.4 mmol), MeCN (1 mL), DMSO (0.6 mmol), 60°C. EWG = electron-withdrawing group.

in 46% yield, probably because of faster β-H elimination, owing to lower steric hindrance.[18c]

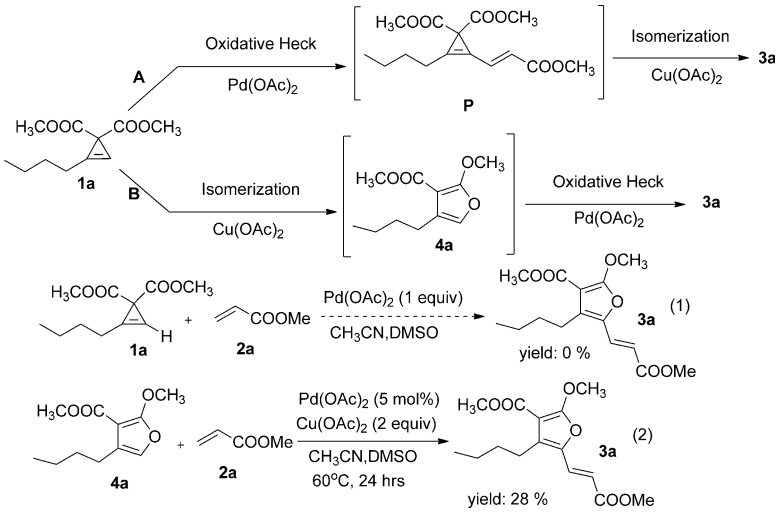
Two possible reaction pathways can be rationalized for this transformation (path **A** and **B**, Scheme 2). To examine the possible palladium-catalyzed C_{sp2}–H activation of cyclopropene, we performed the reaction with one equivalent of $Pd(OAc)_2$ without any other oxidant. We found that no Heck product (**P**) or furan product were produced (Scheme 2, Equation (1)). This result clearly indicated that $Pd(OAc)_2$ could not realize the proposed C–H activation under these condition and ruled out path **A**.

It has been reported that CuI and $Cu(acac)_2$ (acac = acetylacetonate) can catalyze the isomerization of cyclopropene into trisubstituted furan,[14] and we also isolated furan **4a** as the by-product. Recently, several groups have reported the DHRs of furans with different alkenes by using $Pd(OAc)_2$ as an efficient catalyst.[19] These data indicate that the reaction might proceed along path **B**. However, we noticed that the DHR of a furan requires either quite harsh reaction conditions (high temperature, acid additive) or a prolonged reaction time. Thus, furan **4a** and methyl acrylate (**2a**) were subjected to the standard reaction conditions and, to our great surprise, this reaction was very slow and furan **4a** was not consumed, even after 24 h; the final product (**3a**) was obtained in only 28% yield after 24 h. Such a striking contrast in the reaction rate shows that path **B** is not likely.

Therefore, we performed kinetic experiments to probe the reaction mechanism (for details, see the Supporting Information). The standard reaction of compound **1a** with compound **2a** was monitored by crude ^1H NMR analysis after work-up at an indicated time (Figure 1). Cyclopropene **1a** was consumed very fast and some compound **4a** was generated, but it has completely disappeared after 1 h.

According to these data, we proposed a copper/palladium relay mechanism (Scheme 3). It is generally accepted that copper acetate reacts with cyclopropene, thereby generating the copper carbene intermediate **C**, followed by intramolecular cyclization leading to the carbonyl ylide species **D**, which undergoes a demetalation process to afford the furan intermediate **4**, as reported.[14] On the other hand, if the ylide **D** lost HOAc via the six-membered ring transition state **TS1**, a furan copper intermediate (**E**) would be produced. Subsequent transmetalation to generate the key furan–palladium intermediate **F** (possibly stabilized by DMSO), followed by regular insertion into the alkene and β-H elimination, would afford the products. Finally, the Pd^0 is oxidized by $Cu(OAc)_2$ to regenerate the catalyst.

Although we can not currently directly confirm this Cu/Pd relay sequence, this mechanism can explain all of the reaction details: 1) Because two equivalents of $Cu(OAc)_2$ are used, the isomerization step into the furan–copper complex will be very fast, which is in accord with the fast consumption of the cyclopropene; 2) this reaction pathway avoids a C–H metalation step, which normally requires high energy input, and thus the reaction proceeds at a very fast rate; 3) the unreacted furan–copper species **E** will generate furan intermediate **4** during work-up, which is in accord with the parabola shape of this intermediate; 4) the six-membered ring transition state **TS1** is very



Scheme 2. Possible reaction pathway and control experiments.

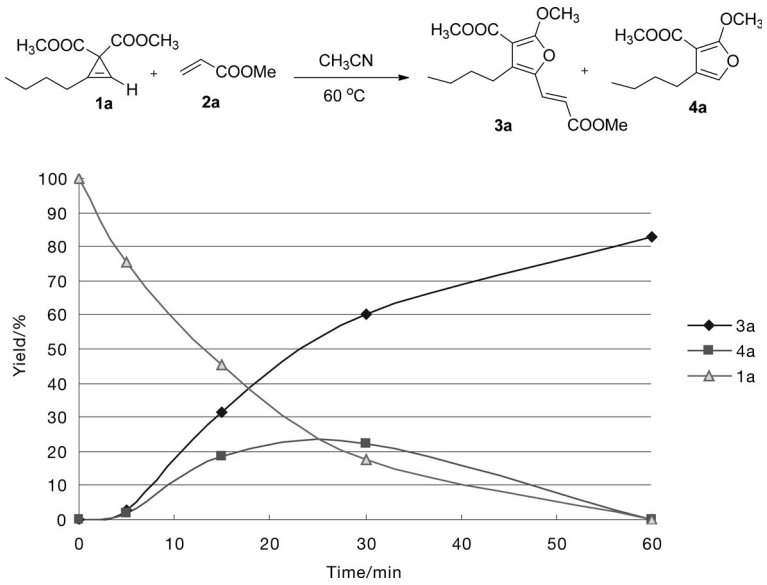
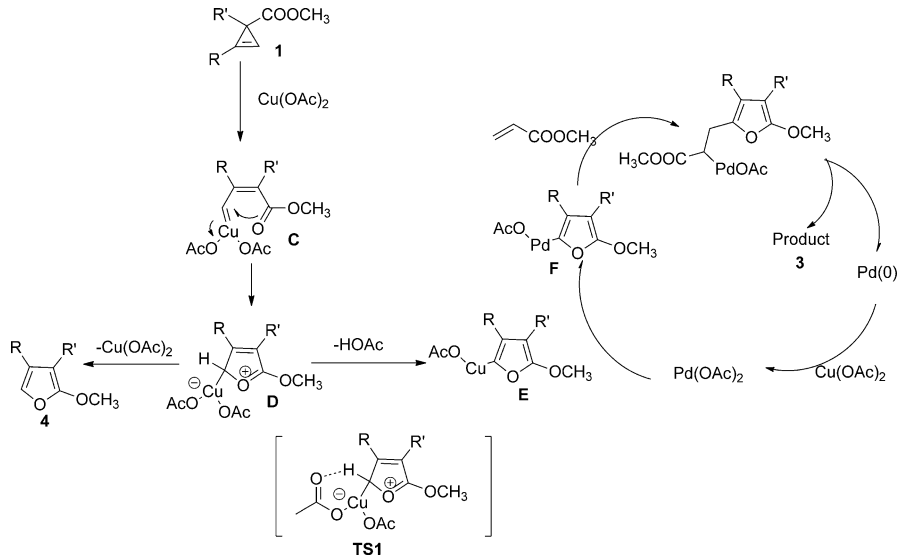


Figure 1. Kinetic study of the cross DHR reaction.



Scheme 3. Proposed relay mechanism for the copper/palladium catalysis.

important for the formation of furan–copper species **E** because other copper compounds, such as $CuCl_2$ and $CuSO_4$, do not work as well as $Cu(OAc)_2$.

In summary, we have developed a convenient and efficient synthesis of tetrasubstituted alkene-functionalized furans from cyclopropenes. An isomerization/olefination cascade sequence was achieved by using copper/palladium relay catalysis. The most important feature of this procedure is the transmetalation relay strategy, which is significantly different from the general C–H activation mode. More importantly, the reaction efficiency is greatly improved by using equivalent amounts of a cheap metal catalyst and catalytic amounts of a precious metal catalyst. These results will provide an alternative insight into reaction design and organic synthesis. Further mechanism investigation and other synthetic applications of this strategy are currently underway in our laboratory.

Experimental Section

A mixture of $Pd(OAc)_2$ (2.24 mg, 0.01 mmol, 5 mmol%) and $Cu(OAc)_2$ (79.6 mg, 0.4 mmol, 2 equiv) was dissolved in MeCN (1 mL) and DMSO (45.6 mg, 0.6 mmol, 3 equiv), then compound **1a** (42.4 mg, 0.2 mmol) and compound **2a** (34.4 mg, 0.4 mmol, 2 equiv) were added. The resulting mixture was stirred at 60 °C until the reaction was complete (by TLC analysis). The reaction mixture was filtered and evaporated under reduced pressure and purified by column chromatography on silica gel to give the pure product (**3a**).

CCDC 905895 (**3a**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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Keywords: copper · cyclopropenes · heterocycles · isomerization · transmetalation

[1] For selected reviews, see: a) B. A. Keay, J. M. Hopkins, P. W. Dibble, in Comprehensive Heterocyclic Chemistry III, (Eds.: G. Jones, C. A. Ramsden), Elsevier, Amsterdam, **2008**, p. 571–623; b) X. L. Hou, H. Y. Cheung, T. Y. Hon, P. L. Kwan, T. H. Lo, S. Y. Tong, H. N, C. Wong, *Tetrahedron* **1998**, *54*, 1955–2020.

[2] For a review, see: a) B. H. Lipshutz, *Chem. Rev.* **1986**, *86*, 795–819.

[3] For recent reviews on the synthesis of furan derivatives, see: a) R. C. D. Brown, *Angew. Chem.* **2005**, *117*, 872–874; *Angew. Chem. Int. Ed.* **2005**, *44*, 850–852; b) S. F. Kirsch, *Org. Biomol. Chem.* **2006**, *4*, 2076–2080; for recent examples, see: c) S. Kramer, T. Skrydstrup, *Angew. Chem. Int. Ed.* **2012**, *51*, 4681–4684; d) C. He, S. Guo, J. Ke, J. Hao, H. Xue, H. Chen, A. Lei, *J. Am. Chem. Soc.* **2012**, *134*, 5766–5769; e) J. Fournier, S. Arseniyadis, J. Cossy, *Angew. Chem. Int. Ed.* **2012**, *51*, 7562–7566; f) P. Lenden, D. A. Entwistle, M. C. Willis, *Angew. Chem.* **2011**, *123*, 10845–10848; *Angew. Chem. Int. Ed.* **2011**, *50*, 10657–10660; g) T. J. Donohoe, J. F. Bower, *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 3373–3376; h) M. Zhang, H.-F. Jiang, H. Neumann, M. Beller, P. H. Dixneuf, *Angew. Chem.* **2009**, *121*, 1709–1712; *Angew. Chem. Int. Ed.* **2009**, *48*, 1681–1684.

[4] G. Minetto, L. F. Raveglia, A. Sega, M. Taddei, *Eur. J. Org. Chem.* **2005**, 5277–5288, and references therein.

[5] For selected examples, see: a) G. Mross, E. Holtz, P. Langer, *J. Org. Chem.* **2006**, *71*, 8045–8049; b) M. A. Calter, C. Zhu, R. J. Lachicotte, *Org. Lett.* **2002**, *4*, 209–212.

[6] For selected examples from alkynes, see: a) F. M. Istrate, F. Gagosz, *Beilstein J. Org. Chem.* **2011**, *7*, 878–885; b) P. A. Allegretti, E. M. Ferreira, *Org. Lett.* **2011**, *13*, 5924–5927; c) M. Egi, K. Azechi, S. Akai, *Org. Lett.* **2009**, *11*, 5002–5005; d) L. Zhao, Z. Guan, Y. Han, Y. Xie, S. He, Y. Liang, *J. Org. Chem.* **2007**, *72*, 10276–10278; e) J. Zhang, H.-G. Schmalz, *Angew. Chem.* **2006**, *118*, 6856–6859; *Angew. Chem. Int. Ed.* **2006**, *45*, 6704–6707; f) A. S. K. Hashmi, P. Sinha, *Adv. Synth. Catal.* **2004**, *346*, 432–438; g) Y.-X. Xie, X.-Y. Liu, L.-Y. Wu, Y. Han, L.-B. Zhao, M.-J. Fan, Y.-M. Liang, *Eur. J. Org. Chem.* **2008**, 1013–1018; for selected examples from allenes, see: h) A. S. Dudnik, V. Gevorgyan, *Angew. Chem.* **2007**, *119*, 5287–5289; *Angew. Chem. Int. Ed.* **2007**, *46*, 5195–5197; i) T. Schwier, A. W. Sromek, D. M. L. Yap, D. Chernyak, V. Gevorgyan, *J. Am. Chem. Soc.* **2007**, *129*, 9868–9878; j) Y. Xia, A. S. Dudnik, V. Gevorgyan, Y. Li, *J. Am. Chem. Soc.* **2008**, *130*, 6940–6941; k) A. W. Sromek, M. Rubina, V. Gevorgyan, *J. Am. Chem. Soc.* **2005**, *127*, 10500–10501; l) L. Peng, X. Zhang, M. Ma, J. Wang, *Angew. Chem.* **2007**, *119*, 1937–1940; *Angew. Chem. Int. Ed.* **2007**, *46*, 1905–1908; m) S. Ma, Z. Yu, *Angew. Chem.* **2002**, *114*, 1853–1856; *Angew. Chem. Int. Ed.* **2002**, *41*, 1775–1778; n) S. Ma, J. Zhang, L. Lu, *Chem. Eur. J.* **2003**, *9*, 2447–2456; o) A. S. K. Hashmi, L. Shwarz, J. H. Choi, T. M. Trost, *Angew. Chem.* **2000**, *112*, 2382–2385; *Angew. Chem. Int. Ed.* **2000**, *39*, 2285–2288; p) A. S. K. Hashmi, *Angew. Chem.* **1995**, *107*, 1749–1751; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1581–1583; q) S. Ma, J. Zhang, *Chem. Commun.* **2000**, 117–118; for selected examples from alklidenecyclopropanes, see: r) S. Ma, L. Lu, J. Zhang, *J. Am. Chem. Soc.* **2004**, *126*, 9645–9660; s) S. Ma, J. Zhang, *Angew. Chem.* **2003**, *115*, 193–197; *Angew. Chem. Int. Ed.* **2003**, *42*, 183–187.

[7] a) H. Ila, O. Baron, A. J. Wagner, P. Knochel, *Chem. Commun.* **2006**, 583–593; b) L. Melzig, C. B. Rauhut, P. Knochel, *Chem. Commun.* **2009**, 3536–3538; c) K. Snégaroff, J.-M. L'Helgoual'ch, G. Bentabed-Ababsa, T. T. Nguyen, F. Chevallier, M. Yonehara, M. Uchiyama, A. Derdour, F. Mongin, *Chem. Eur. J.* **2009**, *15*, 10280–10290.

[8] For one example of the synthesis of alkene-functionalized tetrasubstituted furans, see reference [5a]. For the synthesis of tetrasubstituted furans, see: a) H. Gao, J. Zhang, *Chem. Eur. J.* **2012**, *18*, 2777–2782; b) H. Gao, X. Wu, J. Zhang, *Chem. Eur. J.* **2011**, *17*, 2838–2841; c) G. Zhou, F. Liu, J. Zhang, *Chem. Eur. J.* **2011**, *17*, 3101–3104; d) T. Wang, C.-H. Wang, J. Zhang, *Chem. Commun.* **2011**, *47*, 5578–5580; e) F. Liu, D. Qian, L. Li, X. Zhao, J. Zhang, *Angew. Chem.* **2010**, *122*, 6819–6822; *Angew. Chem. Int. Ed.* **2010**, *49*, 6669–6672; f) Y. Xiao, J. Zhang, *Angew. Chem.* **2008**, *120*, 1929–1932; *Angew. Chem. Int. Ed.* **2008**, *47*, 1903–1906; g) T.-T. Kao, S. Syu, Y.-W. Jhang, W. Lin, *Org. Lett.* **2010**, *12*, 3066–3069; h) H. Cao, H. Jiang, W. Yao, X. Liu, *Org. Lett.* **2009**, *11*, 1931–1933; i) R. Sanz, D. Miguel, A. Martinez, J. M. Alvatez-Gutierrez, F. Rodriguez, *Org. Lett.* **2007**, *9*, 727–730; j) S. R. Mothe, S. J. L. Lauw, P. Kothandaraman, P. W. H. Chan, *J. Org. Chem.* **2012**, *77*, 6937–6947.

[9] For recent reviews, see: a) J. Le Bras, J. Muzart, *Chem. Rev.* **2011**, *111*, 1170–1214; b) Y. Su, N. Jiao, *Curr. Org. Chem.* **2011**, *15*, 3362–3388.

[10] For Pd-catalyzed DHRs, see: a) N. P. Grimster, C. Gauntlett, C. R. A. Godfrey, M. J. Gaunt, *Angew. Chem.* **2005**, *117*, 3185–3189; *Angew. Chem. Int. Ed.* **2005**, *44*, 3125–3129; b) E. M. Beck, N. P. Grimster, R. Hatley, M. J. Gaunt, *J. Am. Chem. Soc.* **2006**, *128*, 2528–2529; c) S. H. Cho, S. J. Hwang, S. Chang, *J. Am. Chem. Soc.* **2008**, *130*, 9254–9256; d) Y.-H. Xu, J. Lu, T.-P. Loh, *J. Am. Chem. Soc.* **2009**, *131*, 1372–1373; e) Y. Su, N. Jiao, *Org. Lett.* **2009**, *11*, 2980–2983; f) H. Yu, W. Jin, C. Sun, J. Chen, W. Du, S. He, Z. Yu, *Angew. Chem.* **2010**, *122*, 5928–5933; *Angew. Chem. Int. Ed.* **2010**, *49*, 5792–5797; g) Y.-H. Zhang, B.-F. Shi, J.-Q. Yu, *J. Am. Chem. Soc.* **2009**, *131*, 5072–5074; h) B.-F. Shi, Y.-H. Zhang, J. K. Lam, D.-H. Wang, J.-Q. Yu, *J. Am. Chem. Soc.* **2010**, *132*, 460–461; i) D.-H. Wang, K. M. Engle, B.-F. Shi, J.-Q. Yu, *Science* **2010**, *327*, 315–319; j) M. Wasa, K. M. Engle, J.-Q. Yu, *J. Am. Chem. Soc.* **2010**, *132*, 3680–3681; k) M. Ye, G.-L. Gao, J.-Q. Yu, *J. Am. Chem. Soc.* **2011**, *133*, 6964–6967; l) Y.-H. Xu, Y. K. Chok, T.-P. Loh, *Chem. Sci.* **2011**, *2*, 1822–1855; m) C. Huang, B. Chattopadhyay, V. Gevorgyan, *J. Am. Chem. Soc.* **2011**, *133*, 12406–12409; n) C. Wang, H. Ge, *Chem. Eur. J.* **2011**, *17*, 14371–14374; o) L. Wang, W. Guo, X. Zhang, X. Xia, W.-J. Xiao, *Org. Lett.* **2012**, *14*, 740–743; p) F. Chen, Z. Feng, C. He, H. Wang, Y. Guo, X. Zhang, *Org. Lett.* **2012**, *14*, 1176–1179; q) Z. Li, Y. Zhang, Z.-Q. Liu, *Org. Lett.* **2012**, *14*, 74–77; r) M. Yu, Y. Xie, C. Xie, Y. Zhang, *Org. Lett.* **2012**, *14*, 2164–2167; s) P. Gandeepan, C.-H. Cheng, *J. Am. Chem. Soc.* **2012**, *134*, 5738–5741; t) B. Schmidt, N. Elizarov, *Chem. Commun.* **2012**, *48*, 4350–4352; u) A. Kubota, M. H. Emmert, M. S. Sanford, *Org. Lett.* **2012**, *14*, 1760–1763; v) C. Wang, H. Chen, Z. Wang, J. Chen, Y. Huang, *Angew. Chem. Int. Ed.* **2012**, *51*, 7242–7245; w) D. Leow, G. Li, T.-S. Mei, J.-Q. Yu, *Nature* **2012**, *486*, 518–522.

[11] For Ru-catalyzed DHRs, see: a) K. Graczyk, W. Ma, L. Ackermann, *Org. Lett.* **2012**, *14*, 4110–4113; b) L. Ackermann, L. Wang, R. Wolfram, A. V. Lygin, *Org. Lett.* **2012**, *14*, 728–731; c) K. Padala, M. Jeganmohan, *Org. Lett.* **2012**, *14*, 1134–1137.

[12] For Rh-catalyzed DHRs, see: a) S. Rakshit, C. Grohmann, T. Besset, F. Glorius, *J. Am. Chem. Soc.* **2011**, *133*, 2350–2353; b) F. W. Patureau, F. Glorius, *J. Am. Chem. Soc.* **2010**, *132*, 9982–9983; c) A. S. Tsai, M. Brasse, R. G. Bergmann, J. A. Ellman, *Org. Lett.* **2011**, *13*, 540–542; d) K. D. Hesp, R. G. Bergman, J. A. Ellman, *J. Am. Chem. Soc.* **2011**, *133*, 11430–11433; e) P. Zhao, R. Niu, F. Wang, K. Han, X. Li, *Org. Lett.* **2012**, *14*, 4166–4169; f) S. H. Park, J. Y. Kim, S. Chang, *Org. Lett.* **2011**, *13*, 2372–2375.

[13] For recent reviews on cyclopropenes, see a) M. Rubin, M. Rubina, V. Gevorgyan, *Chem. Rev.* **2007**, *107*, 3117–3179; b) Z.-B. Zhu, Y. Wei, M. Shi, *Chem. Soc. Rev.* **2011**, *40*, 5534–5563; c) F. Miege, C. Meyer, J. Cossy, *Beilstein J. Org. Chem.* **2011**, *7*, 717–734; d) M.

Rubin, M. Rubina, V. Gevorgyan, *Synthesis* **2006**, 1221–1245; e) I. Marek, S. Simaan, A. Masarwa, *Angew. Chem.* **2007**, *119*, 7508–7520; *Angew. Chem. Int. Ed.* **2007**, *46*, 7364–7376; f) J. M. Fox, N. Yan, *Curr. Org. Chem.* **2005**, *9*, 719–732; for recent advances, see: g) Y. Liu, S. Ma, *Chem. Sci.* **2011**, *2*, 811–814; h) L. H. Phun, J. Aponte-Guzman, S. France, *Angew. Chem. Int. Ed.* **2012**, *51*, 3198–3202; i) Y. Liu, S. Ma, *Org. Lett.* **2012**, *14*, 720–723; j) F. Miege, C. Meyer, J. Cossy, *Angew. Chem.* **2011**, *123*, 6054–6059; *Angew. Chem. Int. Ed.* **2011**, *50*, 5932–5937; k) J. Li, C. Sun, S. Demerzhan, D. Lee, *J. Am. Chem. Soc.* **2011**, *133*, 12964–12967; l) K. Kramer, P. Leong, M. Lautens, *Org. Lett.* **2011**, *13*, 819–821; m) F. Liu, X. Bugaut, M. Schedler, R. Frohlich, F. Glorius, *Angew. Chem.* **2011**, *123*, 12834–12839; *Angew. Chem. Int. Ed.* **2011**, *50*, 12626–12630; n) X. Bugaut, F. Liu, F. Glorius, *J. Am. Chem. Soc.* **2011**, *133*, 8130–8133; o) Z. Zhu, K. Chen, Y. Wei, M. Shi, *Organometallics* **2011**, *30*, 627–632; p) M. S. Hadfield, A. L. Lee, *Chem. Commun.* **2011**, *47*, 1333–1335; q) D. H. T. Phan, K. G. M. Kou, V. M. Dong, *J. Am. Chem. Soc.* **2010**, *132*, 16354–16355; r) C. Li, H. Zhang, J. Feng, Y. Zhang, J. Wang, *Org. Lett.* **2010**, *12*, 3082–3085; s) V. Tarwade, X. Liu, N. Yan, J. M. Fox, *J. Am. Chem. Soc.* **2009**, *131*, 5382–5383; t) S. Chuprakov, M. Rubin, V. Gevorgyan, *J. Am. Chem. Soc.* **2005**, *127*, 3714–3715.

[14] For the related COONa-directed C–H activation of vinyl groups, see: a) R. Giri, J.-Q. Yu, *J. Am. Chem. Soc.* **2008**, *130*, 14082–14083; for the related C–H activation of cyclopropanes, see: b) M. Wasa, K. M. Engle, D. W. Lin, E. J. Yoo, J.-Q. Yu, *J. Am. Chem. Soc.* **2011**, *133*, 19598–19601; c) R. Giri, X. Chen, J.-Q. Yu, *Angew. Chem.* **2005**, *117*, 2150–2153; *Angew. Chem. Int. Ed.* **2005**, *44*, 2112–2115.

[15] For the cycloisomerization of cyclopropenes into furans or other hetrocycles through a carbenoid pathway, see: a) J. Chen, S. Ma, *Chem. Asian J.* **2010**, *5*, 2415–2421; b) S. Ma, J. Zhang, *J. Am. Chem. Soc.* **2003**, *125*, 12386; c) S. Chuprakov, V. Gevorgyan, *Org. Lett.* **2007**, *9*, 4463–4466; d) H. Li, R. P. Hsung, *Org. Lett.* **2009**, *11*, 4462–4465; e) A. Padwa, J. M. Kassir, S. L. Xu, *J. Org. Chem.* **1991**, *56*, 6971–6972; f) A. Padwa, T. J. lacklock, R. Loza, *J. Am. Chem. Soc.* **1981**, *103*, 2404–2405.

[16] DMSO might act as a ligand for activating the Pd catalyst and prevent the formation of Pd black. For details, see: a) B. A. Steinhoff, S. S. Stahl, *J. Am. Chem. Soc.* **2006**, *128*, 4348–4355; b) H. Li, J. Liu, C.-L. Sun, B.-J. Li, Z.-J. Shi, *Org. Lett.* **2011**, *13*, 276–279.

[17] Such a high reaction efficiency is very rare in C–H activations; for one example, see: D. R. Stuart, M. Bertrand-Laperle, K. M. N. Burgess, K. Fagnou, *J. Am. Chem. Soc.* **2008**, *130*, 16474–16475.

[18] For a few examples of oxidative Heck reactions, including those with disubstituted alkenes, see: a) See reference [10u]; b) Z. Fu, S. Huang, W. Su, M. Hong, *Org. Lett.* **2010**, *12*, 4992–4995; c) R. Álvarez, C. Martinez, Y. Madich, J. G. Denis, J. M. Aurrecoechea, A. R. Lera, *Chem. Eur. J.* **2010**, *16*, 12746–12753.

[19] For the DHRs of furan, see: a) Y. Zhang, Z. Li, Z.-Q. Liu, *Org. Lett.* **2012**, *14*, 226–229; b) A. Vasseur, D. Harakat, J. Muzart, J. Le Bras, *J. Org. Chem.* **2012**, *77*, 5751–5758; c) A. Vasseur, J. Muzart, J. Le Bras, *Chem. Eur. J.* **2011**, *17*, 12556–12560; d) C. Aouf, E. Thiery, J. Le Bras, J. Muzart, *Org. Lett.* **2009**, *11*, 4096–4099.

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